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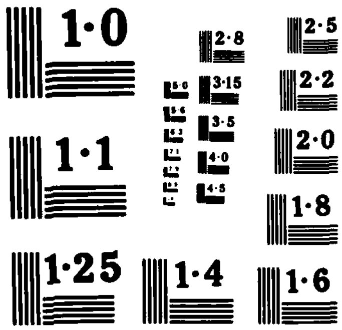
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The effects of water temperature and flavoring on voluntary dehydration (D), sweat electrolyte losses (SEL) and total body electrolyte losses (TBE) were studied in 12 healthy males during six hours of intermittent exercise at 40.6°C DB, 25.5°C WB. Trials involved three water temperatures (6°, 22°, 46°C) and two flavorings (chlorinated and plain). Subjects (Ss) who were presented with 46°C water consumed less ($p<0.001$), had a larger % body weight loss ($p<0.001$), and a D which was 1050 g larger ($p<0.001$) than subjects who consumed 6°C. Sweat rates of the 6°, 22° and 46°C groups were essentially equal. The SEL of potassium (K+)

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and magnesium were not affected by D, whereas significant differences ($p<0.02$, $p<0.04$) in total sweat sodium (Na+) and chloride losses were observed between the 6°and 46°C groups. Urine elect. losses of 6°vs 46°C were significantly different in K+ only ($p<0.02$), in spite of nearly identical urine volumes (260 vs 267 ml.). The TBE indicated that Ss who underwent D to -2.1% (46°C) lost less Na+ ($p<0.03$) but more K+ ($p<0.03$) than Ss who experienced -0.5% D (6°C). Most of the Na+ was secreted in sweat, while K+ losses primarily originated in urine. Based on 24 hour projections of total body electrolyte balance, K+ depletion was considered to be more likely than Na+ depletion because food can be easily supplemented with sodium chloride.
INDEX TERMS: sodium, potassium, sweat, urine, body weight, water consumption.

VOLUNTARY DEHYDRATION AND ELECTROLYTE LOSSES DURING PROLONGED EXERCISE IN THE HEAT

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ABSTRACT

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INTRODUCTION

The effects of water temperature and flavor on drinking behavior in animals has been reviewed by several authors (11,22,32). Although the mechanisms that control drinking behavior in humans are not well defined (13,25) it has been established that the temperature and flavor of drinking water are critical factors in its acceptance and consumption by humans (1,4,15). A behavioral component of fluid intake (15) apparently works in consort with the Na+-osmotic-vasopressin pathway and the renin-angiotensin II system (14) to stimulate, maintain and terminate human water intake. In addition, it is clear that thirst does not always stimulate sufficient drinking to replace fluid losses incurred by profuse sweating and urination. During exercise in the heat or daily living in hot environments, a body weight deficit of 1-4.5% can occur even though water is provided ad libitum (1,3,15). This phenomenon has been named voluntary dehydration (1,12,29).

Little is known about the impact of drinking behavior on sweat rate or sweat electrolyte losses, although research on sweat gland function during exercise in the heat began in the early 1930s (24). Electrolyte losses in sweat are of interest because of the nutritional implications of potential electrolyte deficits (6,7,8,31). Of further interest are the effects of many factors on sweat electrolyte composition. Robinson and Robinson have identified seven factors which alter the electrolyte concentration of human sweat (24).

The present investigation offered a unique design to study

water and electrolyte balance because water palatability resulted in varying levels of water consumption. This strong relationship between water acceptance and total consumption also is seen during desert field living (1). The impact of ad libitum water intake on physiological responses were measured in a controlled laboratory setting. The effects of drinking water temperature (6°, 22°, 46° C) and flavor (chlorine vs plain) on water consumption, voluntary dehydration, and electrolyte losses were assessed. These temperatures were chosen for reasons described elsewhere (26); chlorine was chosen as a flavoring because it has a characteristic flavor and is customarily found in drinking water. Additionally, the nutritional impact of total body electrolyte losses were evaluated.

METHODS

The subjects of this study were twelve unacclimatized males whose physical characteristics (mean + SE) were: 173.8±2.1 cm height, 72.75±2.49 kg nude body weight, 1.87±0.04 m^2 body surface area, and 23±2 yr. These subjects reported to a climatic chamber for six hours on each of two nonconsecutive days in mid-December. After eating breakfast at 0700 hours, subjects were weighed nude (±50 g) and while dressed in shorts, socks, underpants, and sneakers.

Prior to the onset of exercise in the climatic chamber, subjects were fitted with standard ECG electrodes, a rectal probe, and three-point skin thermocouples (chest, arm, leg) which

permitted heart rate, rectal temperature, and mean weighted skin temperature (5) to be monitored every four minutes. Exercise bouts consisted of walking on a motorized treadmill for 30 minutes each hour (1.34 m/sec, 5% grade, 14.5 km walked and 724 m climbed/6 hr), and were followed by 30 minutes of sitting. Six work-rest cycles were conducted each day under mean chamber conditions of 40.6±0.7°C dry bulb, 25.5±0.8°C wet bulb, 30.0±0.7°C WBGT, and 1.0±0.1 m/sec wind velocity.

Subjects were randomly assigned to one of three water temperature treatment groups (6°, 22°, or 46°C) and participated twice; during one session the water was chlorinated, during the other it was not chlorinated (plain). Plain water contained less than 1 ppm of chlorine and chlorinated water contained 5 ppm. Coded canteens were placed within the reach of subjects and were refilled every 30 minutes. Water consumption was measured (±1 g) at the end of each exercise and rest period. Subject grouping (four subjects per treadmill) and the order of plain vs chlorinated treatments were randomized, and were conducted in a double-blind fashion. All data are expressed as mean (±SE). The data from one 46°C trial were eliminated due to subject noncompliance with instructions.

Urine samples were collected in clean, inert containers during each of the six rest periods and immediately following the six hour trial. Samples were analyzed for volume, osmolality, specific gravity, sodium concentration, and potassium concentration. Plasma osmolality was analyzed in blood samples taken from an antecubital

vein prior to the first exercise bout and 20 min after the completion of the final exercise bout.

Body weight differences recorded after each work bout and after each rest period were used to calculate sweat losses. Sweat rates were corrected for water intake, food intake (lunch during the third rest period), and urine losses.

Sweat electrolytes were collected after the post-exercise blood sample, using the whole body washdown technique described by Vellar (31). Subjects showered thoroughly before trials (no soap) and their clothing was laundered so that it contained no measurable electrolytes. During work bouts all dripping sweat, which was minimal due to the dry conditions, was blotted from the skin with electrolyte-free towels. The subjects, towels, and clothing were washed with a known volume of deionized water (3.83 l) and aliquots were analyzed for sodium, potassium, chloride, and magnesium.

Because statistical analysis of 35 variables indicated that no significant differences existed between the plain and chlorinated flavoring treatments (except for total magnesium), the chlorinated and plain values were combined (except total mEq sweat magnesium). Group comparison t-tests (n=8) for the difference between hour 6 means (33) were performed to evaluate the effects of drinking water temperatures (n=8 trials per temperature). The data of the three drinking water treatment groups (6°,22°,46°C) were also combined to produce a correlation matrix for all measured variables (n=23 trials). Multiple linear regression analyses were computed for sweat sodium and sweat potassium concentration.

RESULTS

Fluid Balance

Water consumption data for the three temperature treatments are presented in Figure 1a. Although the intake of 6° and the 22°C water was not significantly different, both were significantly greater at hour 6 than the 46°C water intake ($p<.001$ and $p<.01$, respectively). The rate of water intake (ml/30 min, Fig. 1) clearly indicated that the difference in cumulative water intake between the three drinks occurred primarily during the first two work-rest cycles; from 2-6 hours, the rate of water intake was similar for all water temperatures.

Fig. 1

The mean per cent body weight differences (Δ BW%) at the end of 6°, 22°, and 46°C trials were: -0.5(±0.2)%, -1.0(±0.2)%, and -2.1(±0.2)%, respectively. The following statistical differences in Δ BW% were calculated between treatment groups: 6° vs 46°C - $p<.001$; 22° vs 46°C - $p<.001$.

Voluntary dehydration in this investigation was defined as: (sweat loss) + (urine loss) - (water consumption). The mean voluntary dehydrations of the 6° and 22°C trials were not statistically different (750±130 g vs 790±190 g), but the voluntary dehydration while drinking 46°C water was significantly larger (1800 ± 90 g) than the 6° and 22°C treatments (both $p<.001$).

Plasma osmolality exhibited no significant inter-group differences, but correlated significantly with six hour water intake ($r=+0.66$, $p<.005$), change in body weight ($r=+0.43$, $p<.05$),

and voluntary dehydration ($r=+0.47$, $p<0.02$).

A comparison of water losses via sweating (Figure 2) clearly illustrated that fluid losses due to sweating were not significantly affected by water consumption. Sweat rate was not significantly correlated with mean weighted skin temperature, final rectal temperature, or change in rectal temperature.

Electrolyte Losses

Sweat potassium (K^+) and magnesium (Mg^{++}) values did not differ ($p>.05$) between the three water temperature treatments. **Table 1** However, Table 1 describes the significant differences between experimental groups in the sodium (Na^+) and chloride (Cl^-) concentrations of sweat, as well as the total mEq of Na^+ and Cl^- lost during the six hours of exercise and rest. These differences were observed in spite of no differences in sweat rate between **Fig. 2** groups (Figure 2). The correlation coefficient between sweat Na^+ and Cl^- concentrations was $r= +0.98$. Sweat Na^+, Cl^-, K^+, and Mg^{++} values were not significantly correlated with either mean weighted skin temperature or rectal temperature. Similarly, sweat rate was not significantly correlated with any sweat electrolyte except total K^+ ($r=+0.69$, $p<.001$).

The mean urine volumes of subjects during six hours of intermittent exercise drinking 6°, 22°, and 46°C water were not significantly different. The only urine electrolyte which differed between treatment groups was K^+ concentration (6° vs 46°C, $p<0.02$). This difference existed in spite of the similarity in 6° and 46°C mean urine volumes (260 ± 78 vs 267 ± 17). Urine K^+ concentration was

significantly correlated with the following factors: water intake ($r = -0.68$), voluntary dehydration ($r = +0.79$), and % change in body weight ($r = +0.60$).

Fig. 3 Figure 3 illustrates the total six hour Na+ and K+ losses (urine + sweat). It is apparent that most of the Na+ was secreted in sweat, while the majority of the K+ losses originated in urine. Significant between-group differences in Na+ loss ($p<0.03$) and loss ($p<0.02$) occurred between 6° and 46°C water. The total electrolyte losses (urine + sweat) represented 3.5-5.1% of the exchangeable Na+ in the body and 1.1-1.5% of the exchangeable K+, when whole body reservoirs were estimated at 41mEq Na+ and 45mEq K+ per kg body weight (10).

Sweat Electrolyte Variability

The inter-subject variability of sweat K+ was much smaller than that of sweat Na+ (1.7-4.8 mEq K+/l vs 12.7-46.7 mEq Na+/l). This finding has been reported previously (24,31) and was not surprising. To determine the factors which contributed to the variability of sweat electrolyte concentration, two multiple linear regression equations were computed, using the dependent variables of sweat K+ and sweat Na+ concentration. The independent variables were: % change in body weight, change in rectal temperature, change in mean weighted skin temperature, water intake, voluntary dehydration, sweat rate, plasma osmolality and change in plasma osmolality.

The multiple linear regression equation for sweat K+ concentration accounted for 82% of the variability by using four

independent variables, and was significant at the $p < .001$ level. This equation took the form of

$$\begin{aligned} Y \text{ potassium conc., mEq/l} = \; & -18.40647 \\ & -0.00006(\text{voluntary dehydration}) \\ & +0.07723(\text{plasma osmolality}) \\ & -0.42249(\text{change in body weight \%}) \\ & -0.05986(\text{change in plasma osmolality}). \end{aligned}$$

(equation 1)

The addition of five other independent variables to this regression equation only accounted for an additional 1% of the variability in sweat potassium concentration.

The regression equation for sweat Na+ concentration accounted for 49% of the total variability. No combination of the 35 variables satisfactorily predicted sweat Na+ concentration ($p > .05$).

DISCUSSION

The results of this study indicate that the temperature of drinking water directly affects fluid balance in exercising subjects and supports the findings of other studies (1,15). The subjects who were presented with 46°C water (when compared to the 6° C group) consumed significantly less water (Figure 1), had a larger % body weight loss and a greater voluntary dehydration, yet similar sweat rates (Fig. 2). Ladell (19) has also reported that water intake has no effect on sweat rate until water deficits reach 2.5 liters. Furthermore, this study demonstrated that a significant

difference existed between the 6° and 46°C groups, when total Na+ and Cl- losses were compared. For these reasons, the following discussion focuses on the distinctions between the 6° and 46°C treatments.

Sweat Electrolyte Losses

Robinson et al. (23,24) cite several investigations which report that local sweat Cl- levels increased as sweat rate increased. This same relationship would also be expected between Na+ and sweat rate because nearly all Na+ in sweat is combined with Cl- ($r=+0.98$). The data of the present study, however, indicated that this relationship between sweat rate and Na+ or Cl- did not exist during the six hours of intermittent exercise; only K+ losses were related to sweat rate ($r=+0.69$, $p<.001$). Because the studies cited above (24) involved brief, local electrolyte collections (rubber gloves, arm bags, filter paper) it is unlikely that these findings can be applied to six hour trials or to whole body washdowns (18,21,30). In addition, it is known that hourly sweat electrolyte concentrations fluctuate during six hours of continuous thermal stimulation (9).

Although the results of this investigation did not explain the 6° vs 46°C differences observed in sweat Na+ and Cl- losses (Table 2), the sweat gland electrolyte regulatory process (24,27) must have been involved because sweat rates were essentially identical (Figure 2). Schwartz and Thaysen (28) have hypothesized that both Na+ and K+ are delivered into a precursor solution in the sweat gland and that Na+, but not K+, is reabsorbed. During six hours of

sweating, Dobson (9) has observed that sweat glands secrete Na+ during the first 2 hours but later actively reabsorb Na+ (hours 2-6), and that the concentration of K+ is constant during hours 1-4, but increases during hours 5 and 6. Thus, the mechanisms that regulate Na+ and K+ in the sweat gland appear to be independent of each other (2). There are even indications that K+ concentration in sweat may vary inversely with Na+ concentration (24). These observations support and clarify our findings regarding Na+ and K+ losses, as depicted in Table 1 and Figure 3.

Based on multiple linear regression analysis, the four independent variables of equation 1 indicated that sweat K+ was significantly related ($p<.001$) to water loss variables (voluntary dehydration, % change in body weight) and to plasma osmolality. However, the physiological associations between fluid consumption and the regulation of sweat electrolytes involve many intervening steps. Evidently, some combination of voluntary dehydration and plasma osmolality may affect sweat K+ concentration. In contrast, none of the 35 variables measured herein were significantly correlated with sweat Na+ concentration.

Total Body Electrolyte Losses

The nutritional impact of the total body electrolyte losses (urine + sweat) experienced by these twelve subjects must also be considered. Total Na+ losses ranged from 72-244 mEq, while total K+ losses ranged from 23-70 mEq (Figure 3) during six hours of intermittent exercise. The mean six hour sweat loss (n=23 trials) was 3470 g. Assuming sweat losses of 11 liters per 24 hours in a

"worst case" desert scenario (24), and assuming constant 24 hour urinary electrolyte losses, the projected daily Na+ losses of our 12 unacclimatized subjects would range from 242-512 mEq/24 hr, while K+ losses would range from from 77-264 mEq /24 hr.

Comparing these 24 hour losses to the normal daily U.S. intake (20) of Na+ and K+ (26-153 mEq Na+ and 50-100 mEq K+), or to three military C-rations (16) per day (256 mEq Na+ and 89 mEq K+), it is clear that most of our subjects would require dietary salt supplements in their unacclimatized state. Heat acclimatization would decrease Na+ and Cl- losses in sweat and urine but would have little effect on K+ or Mg++ losses (2). This would reduce the need for Na+ supplementation but still would result in large K+ deficits.

Considering the "worst case" electrolyte losses in a desert scenario, our subjects would require 256 mEq of Na+ and 175 mEq of K+ supplements per day. Although this Na+ requirement could be met by acclimatized persons using the salt packets supplied with C-rations (12 g NaCl), the K+ requirement would not be met by eating three field rations per day.

Previous investigations found no indication of K+ depletion during short-term exercise in the heat (8) or during consecutive days of 90 minute exercise bouts in the heat (2). However, when daily heat exposure was prolonged, or when subjects lived continuously in the desert, K+ depletion was reported (17).

SUMMARY

In summary, this investigation has demonstrated that the

temperature of drinking water affects water consumption, and that voluntary dehydration may affect sweat electrolyte and total body electrolyte losses. When subjects voluntarily dehydrated to -2.1% of initial body weight (46°C group), they lost significantly less total body Na+ but more total body K+ than subjects who dehydrated to -0.5% body weight (6°C group). This phenomenon was observed in spite of the similar sweat rates and urine volumes of the 6°C and 46°C groups. The concentrating mechanism of the sweat gland was discussed as a probable cause of differential sweat electrolyte secretions. The % change in body weight, voluntary dehydration, plasma osmolality, and change in plasma osmolality accounted for 82% of the variability in sweat K+ concentration; the reason for sweat Na+ concentration differences was not readily apparent. The nutritional impact of 24 hour total electrolyte losses (urine + sweat) also was discussed. Using normal U. S. or military field diets, expected K+ and Na+ deficits were calculated for a 24 hour period under "worst case" climatic conditions. It was noted that K+ depletion may be more of a problem than Na+ depletion during extended heat and exercise exposure because food may be supplemented easily with sodium chloride.

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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TABLE 1 - SUMMARY OF SWEAT ELECTROLYTE STATISTICAL ANALYSES

Sweat Electrolyte Measurement	Unit	Water Temperatures		
		6^{o} VS 22^{o}	6^{o} VS 46^{o}	22^{o} VS 46^{o}
Sodium Concentration	mEq/1	$p < .01$	$p < .02$	NS
Chloride Concentration	mEq/1	$p < .03$	$p < .04$	NS
Total sodium loss	mEq	NS	$p < .02$	NS
Total Chloride loss	mEq	NS	$p < .04$	NS

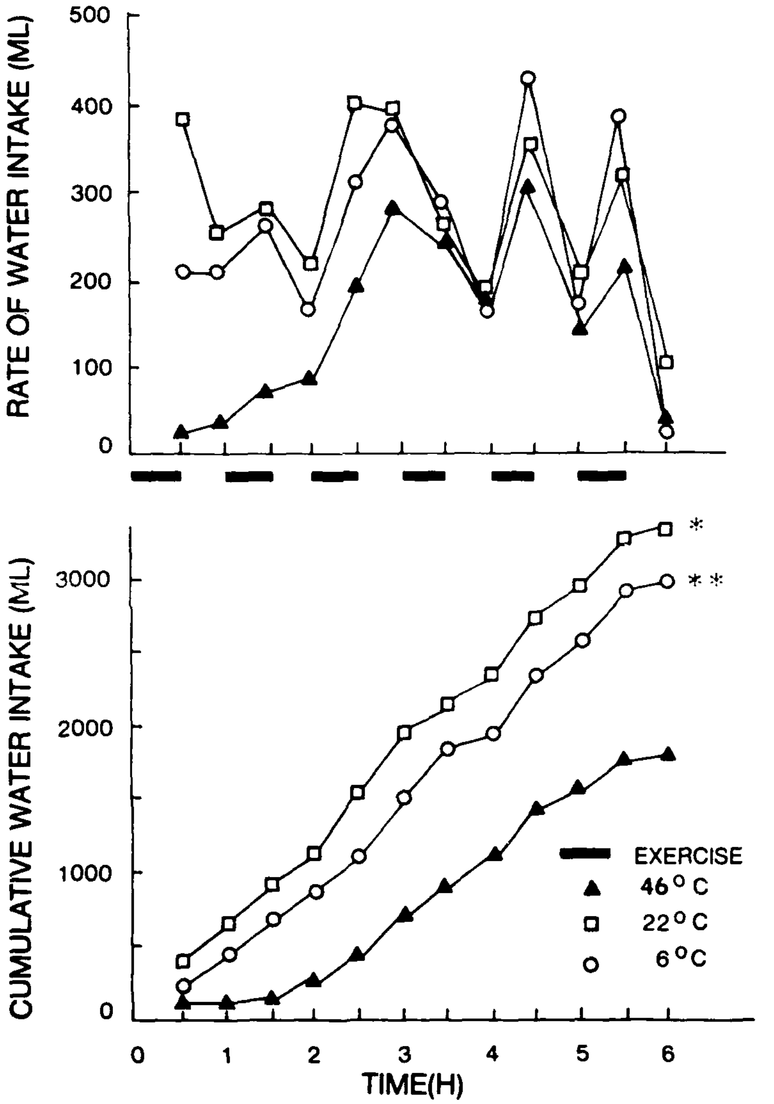
NS - not significant at $p < .05$ level

Potassium and magnesium values were not affected by varying levels of voluntary dehydration.

FIGURE TITLES

Figure	Title
1	Water consumption of groups drinking 6°, 22°, and 46°C water.
2	Sweat rate and cumulative sweat loss during 6 hour trials.
3	Total Na+ and K+ losses (urine + sweat) of 6°, 22°, and 46°C treatment groups.

FIG. 1



* SIGNIFICANTLY GREATER THAN 46° (P< .001) AT HOUR 6

** SIGNIFICANTLY GREATER THAN 46° (P< .01) AT HOUR 6

FIG. 2

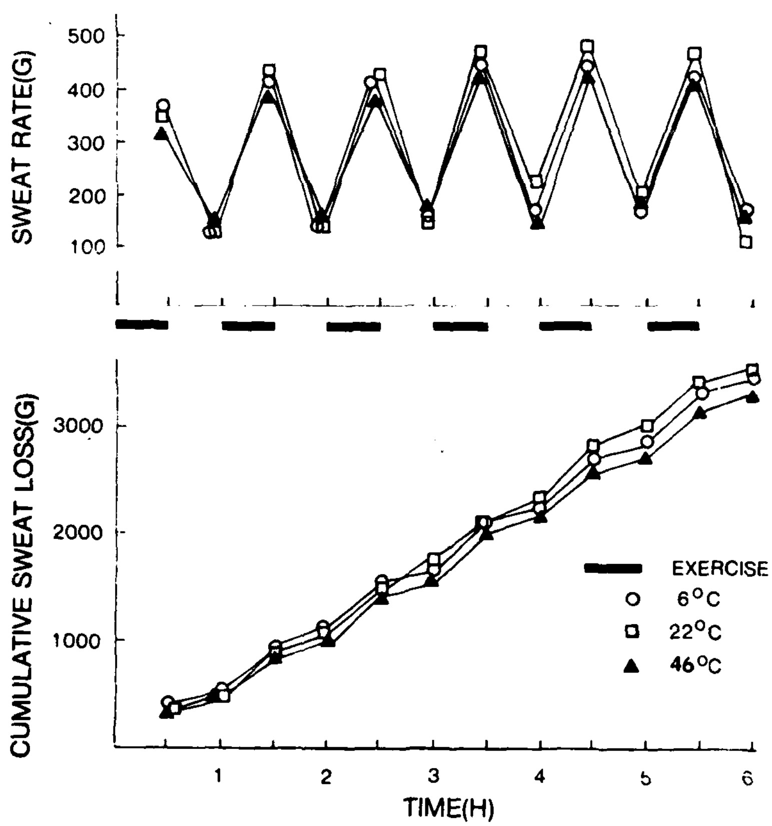
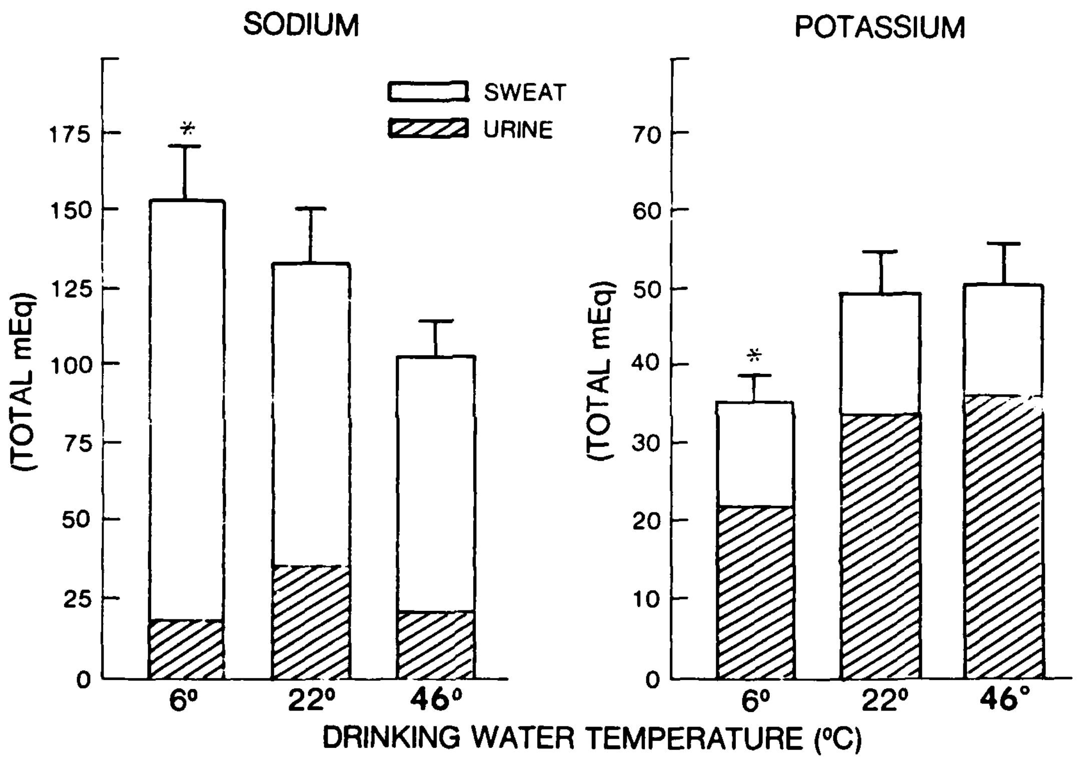

SWEAT RATE(G)
500
400
300
200
100
CUMULATIVE SWEAT LOSS(G)
3000
2000
1000
EXERCISE
6°C
22°C
46°C
1
2
3
4
5
6
TIME(H)

FIG. 3



* SIGNIFICANTLY DIFFERENT FROM 46° (p >0.03)

END

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